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Author(s): Smith, John R.; Garcia, Michael R; Ormond, Eugene C; Parrales, Martin F; Flores, Paul A; Hogge, Keith W; Huber, Steven R; Mitchell, Stephen E; Perez, Jesus R; Romero, Thomas A; Truong, Hoai-Tam V

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Cygnus Performance on Vega

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John R. Smith
Los Alamos National Laboratory

Michael R. Garcia, Eugene C. Ormond, Martin F. Parrales
Sandia National Laboratories

Paul A. Flores, Keith W. Hogge, Steven R. Huber,
Stephen E. Mitchell, Jesus R. Perez,
Thomas A. Romero, Hoai-Tam V. Truong
Mission Support and Technical Services

INTRODUCTION

The Cygnus Dual Beam Radiographic Facility consists of two identical radiographic sources, Cygnus 1 and Cygnus 2, each with the following specifications: 4-Rad dose at 1 m, 1-mm spot size, 50-ns pulse length, and 2.25-MeV endpoint energy. Cygnus 1 and 2 have been used for radiography of subcritical experiments at the Nevada National Security Site (NNSS) since 2004. The Cygnus Facility is located in an underground tunnel complex named U1a. The Cygnus sources were developed as a primary diagnostic for these experiments. The first subcritical experiment to utilize Cygnus, Armando, was executed on May 25, 2004. Since Armando, several other subcritical experiments have been executed in front of Cygnus, as well as physics experiments and plutonium calibration tests. Inherently, subcritical experiments are single-shot, high-value events. Three elements represent key metrics by which to gauge Cygnus performance – Reliability, Record, and Reproducibility. This report describes Cygnus performance in terms of these elements for the latest project experiment, Vega. Vega is the subcritical experiment for the project series Lyra.

Each Cygnus machine has 5 major components as shown in Fig. 1: Marx Generator, Pulse Forming Line (PFL), Coaxial Transmission Line (CTL), 3-cell Inductive Voltage Adder (IVA), and Rod Pinch Diode (RPD). Each machine is independently triggered and may be fired in completely separate tests (staggered mode), or in a single test in which both machines are fired with sub-second separation between pulses (dual mode). Cygnus operates as a single-shot machine since on each pulse the diode electrodes are destroyed. After each shot, the diode is vented to atmosphere, cleaned, and new electrodes are inserted. Normally there are two shots per day on each machine.

Cygnus uses a “Rod Pinch Diode” geometry where the cathode consists of an aluminum plate with an on-center aperture, and the anode is a tungsten rod which threads the aperture and extends beyond its downstream face (Fig. 2). The electrodes are enclosed in a vacuum “hat”. Electrons emanate from the cathode aperture and collide with the anode rod to produce bremsstrahlung x-rays. The majority of electrons pinch onto the rod in a location downstream of the anode due to the self-magnetic force, hence the name Rod Pinch Diode.

Thermoluminescent dosimeters (TLDs) are the primary diagnostic for Cygnus performance. Dosimeter locations are shown in Fig. 3. The center location was used for the data presented in this paper.

For perspective, photos of the diode hardware are given in Figs. 4 and 5. In Fig. 4 the Cygnus diode and tungsten collimator hardware is showcased with the zero-room barrier as a back-drop. In Fig. 5 close-ups of the cathode plate and anode rod are shown.

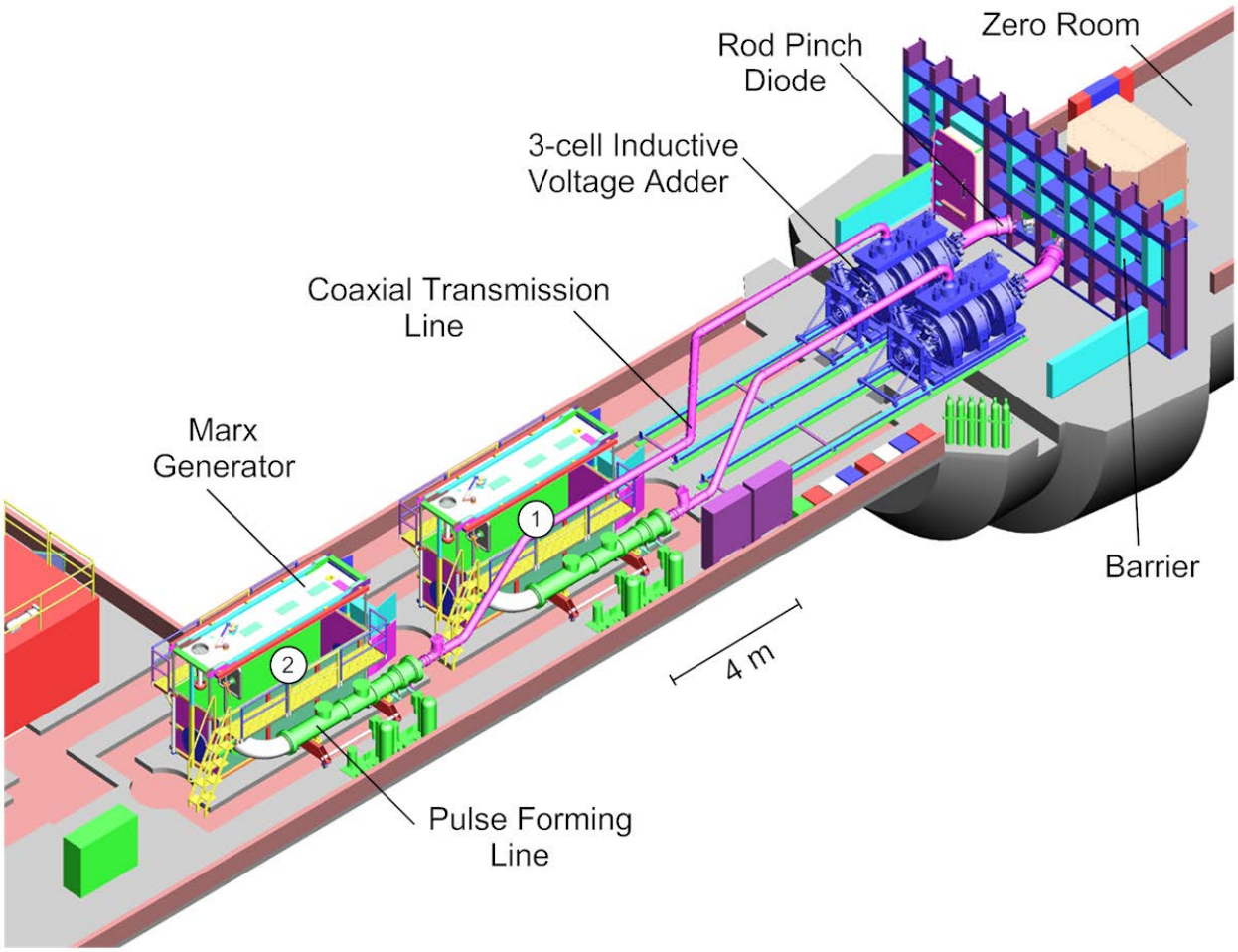


Figure 1. **Cygnus 1 & 2 installation at U1a showing the five major pulsed power components, barrier, and zero room.**

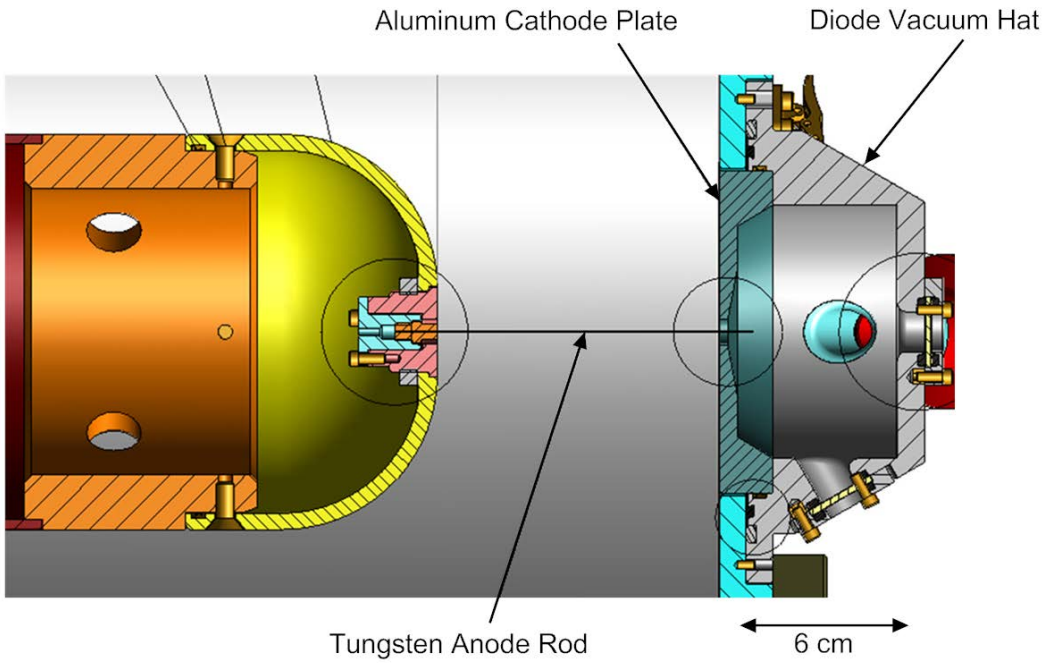


Figure 2. Rod pinch diode geometry.

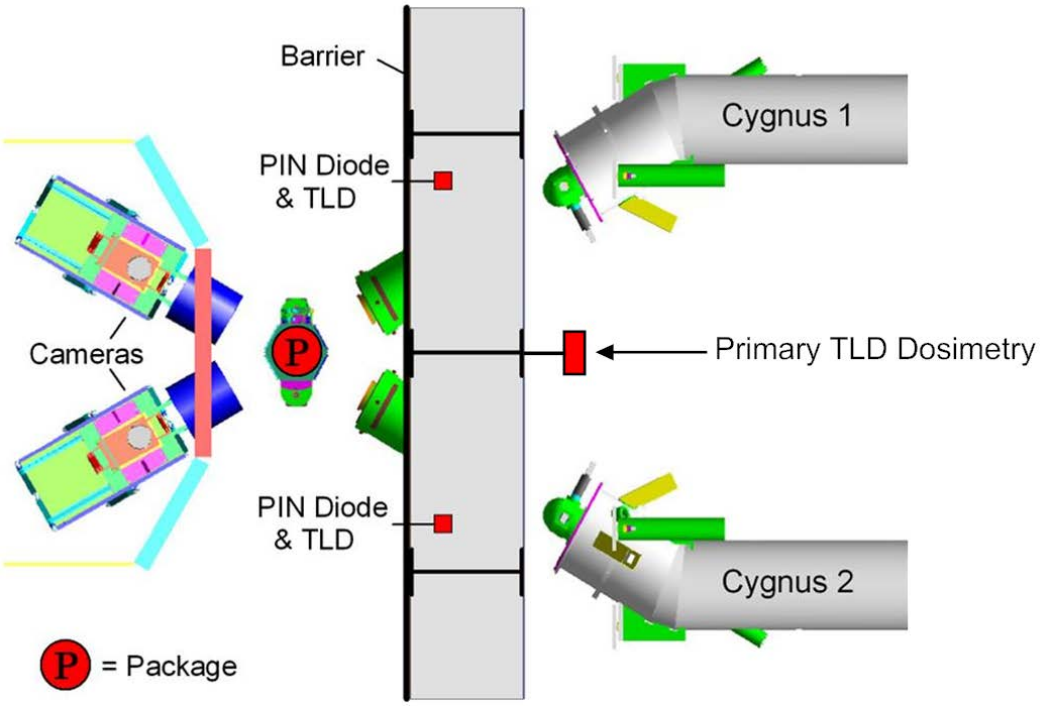
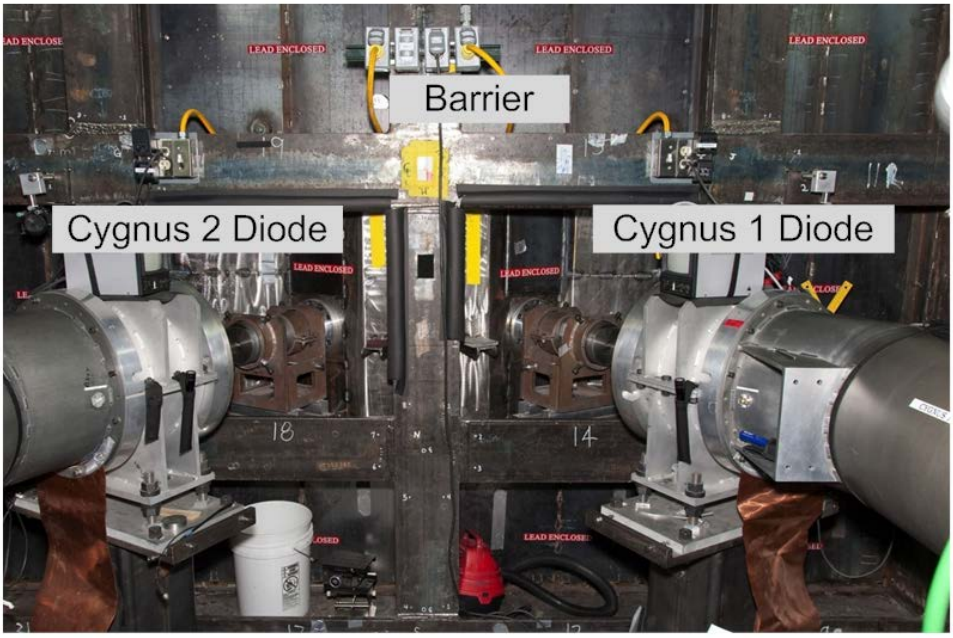


Figure 3. Thermoluminescent dosimeter locations.

(a)



(b)

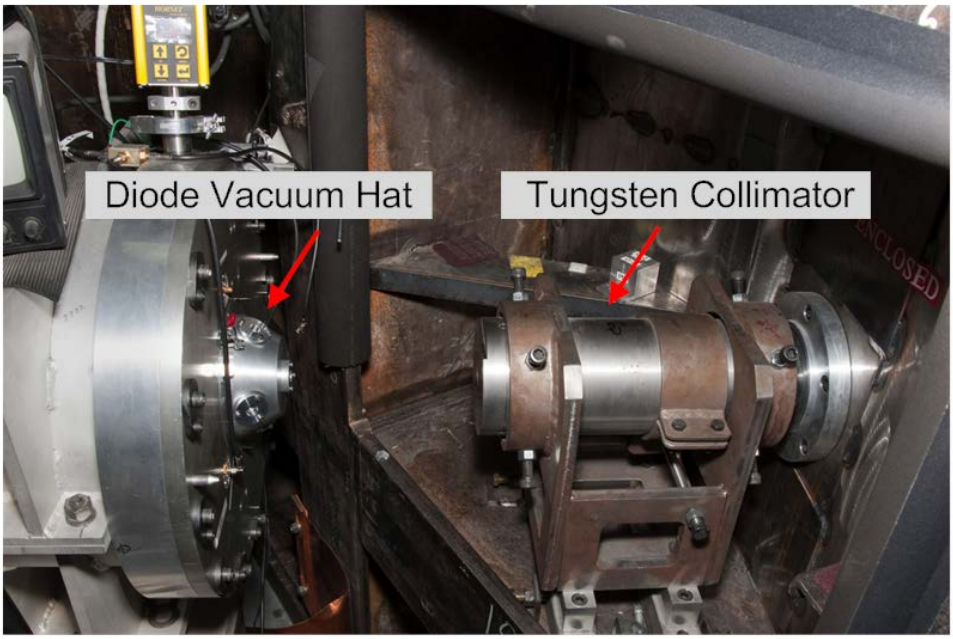
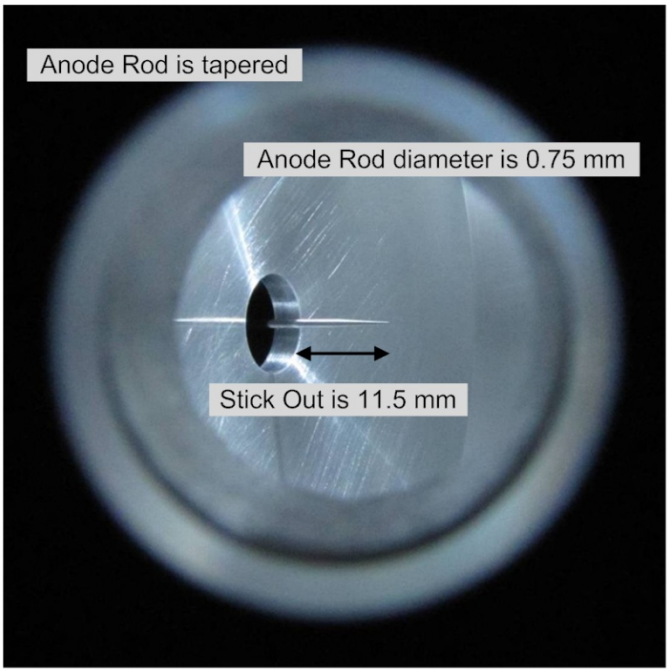


Figure 4. **Photos of: (a) both Cygnus 1 & 2 diodes in front of the barrier and, (b) the Cygnus 2 diode vacuum hat and tungsten collimator.**

(a)



(b)

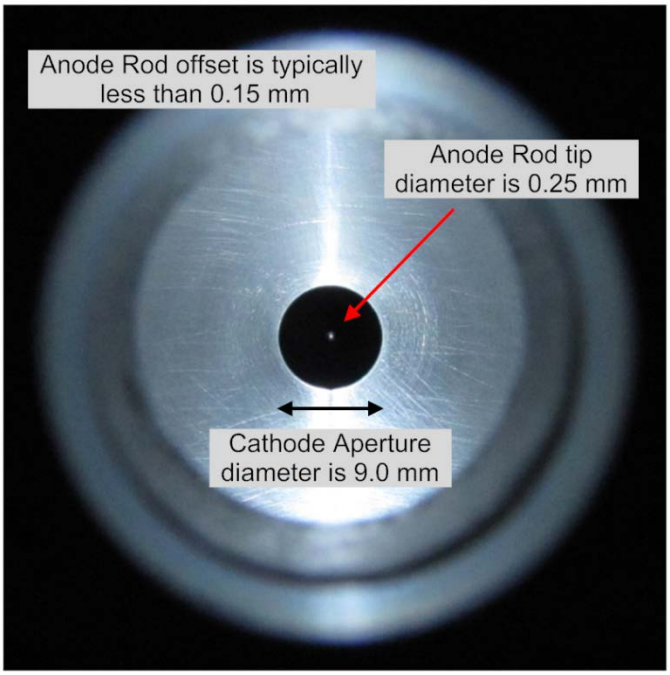


Figure 5. Photos of the cathode plate and anode rod taken from the: (a) diode side window, and (b) diode end window.

PERFORMANCE MODEL

A quantitative performance measurement is valuable for tracking and maintaining Cygnus preparedness. Accordingly, the following model with three metrics has been developed and is described below. We first introduce two definitions of parameters that feed in to the model metrics.

First, a grading tool for Cygnus shots has been defined as shown in Table I. It uses percent of design dose (4.0 Rad) as a standard for performance. As a "rule of thumb" all shots above 2.8 Rads produce useable radiographs.

Table I. Grade Definitions

Grade	Range (% of Design)	Range (Rad)
A^+	> (+10%)	> 4.4
A	(-10%) to (+10%)	3.6 to 4.4
B	(-20%) to (-10%)	3.2 to 3.6
C	(-30%) to (-20%)	2.8 to 3.2
F	< (-30%)	< 2.8

Second, for an SCE there are three meaningful shot periods as shown in Table II. The Historical and Readiness Periods include shots leading up, but not including, the SCE shot, and are long and short term predictors of success on the SCE shot. The long/short term distinction is made to incorporate a timeliness factor into the performance assessment that is meaningful for operations evaluation.

Table II. Period Definitions

Period (Shots)	Description
100	Historical
10	Readiness
1	SCE

There are three key metrics to gauge Cygnus performance – Reliability, Record, and Reproducibility. These metrics all incorporate the grade and period elements as shown in Table III. Reliability is the success fraction, in percent, using 2.8 Rads as the cutoff value for successful shots. Record is the sample mean ($\bar{d}$) using 3.6 Rads as the cutoff value for included shots. Reproducibility is the sample standard deviation (s) using 3.6 Rads as the cutoff value for included shots. The equation for each metric is given below where "A" denotes both A and A^+ shots.

(1) $$Reliability = \frac{A + B + C}{A + B + C + F} * 100\%$$

(2) $$Record = \bar{d} = \frac{1}{A}\sum_{i=1}^{A}(d_A)_i$$

(3) $$Reproducibility = s = \left(\frac{1}{A-1}\sum_{i=1}^{A}[(d_A)_i - \bar{d}]^2\right)^{1/2}$$

A = total number grade A and A^+ shots
B = total number grade B shots
C = total number grade C shots
F = total number grade F shots
$\bar{d}$ = sample mean dose
s = sample standard deviation dose

Table III. Cygnus Performance Metric Summary

Element	Value	Grades Used	Periods Used	Contiguous
Reliability	Success Fraction	A^+ A B C F	100 10 1	Yes
Record	Sample Mean	A^+ A	100 10 1	No
Reproducibility	Sample Deviation	A^+ A	100 10 1	No

GAUSSIAN DISTRIBUTION

The A and A$^+$ data is fit to a Gaussian distribution (Equation 4) in Fig. 6. Here the data is from a 100-shot generic Cygnus dose distribution.

(4) $$N(d) = N_0 \ \exp\left[-\frac{1}{2}\left(\frac{d-\bar{d}}{\sigma}\right)^2\right]$$

N = number shots
$\bar{d}$ = mean dose
σ = standard deviation dose

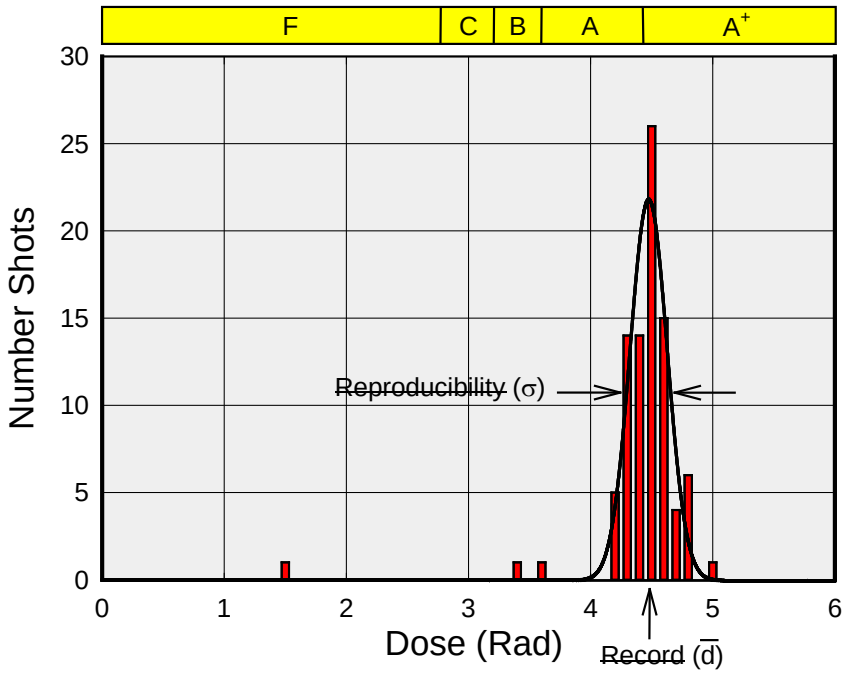


Figure 6. Cygnus dose distribution on a generic series for a 100-shot sample. The A and A$^+$ data are fit to a Gaussian distribution.

Gaussian fit results for Record ($\bar{d}$) and Reproducibility (σ) are given in Table IV for the 100-shot Vega period. These Gaussian model results compare favorably to the corresponding data results of Tables V and VI. Therefore the Gaussian distribution model may be used to accurately represent Cygnus performance.

Table IV. Gaussian fit results for Cygnus 1 and Cygnus 2.

Shot Type	Period	Percent	Dose (Rad)	Dose (Rad)
		Reliability - Grades/All - Contiguous/Yes	Record - Grades/A$^+$ & A - Contiguous/No	Reproducibility - Grades/A$^+$ & A - Contiguous/No
Gaussian Fit - Cygnus 1	100 Shots - Historical	----------	4.36	± 0.17
Gaussian Fit - Cygnus 2	100 Shots - Historical	----------	4.17	± 0.16

VEGA DOSE DISTRIBUTIONS

Dose distributions on Vega for a 100-shot sample are given in Fig. 7. Notably, all shots are high level grade A or grade A^+.

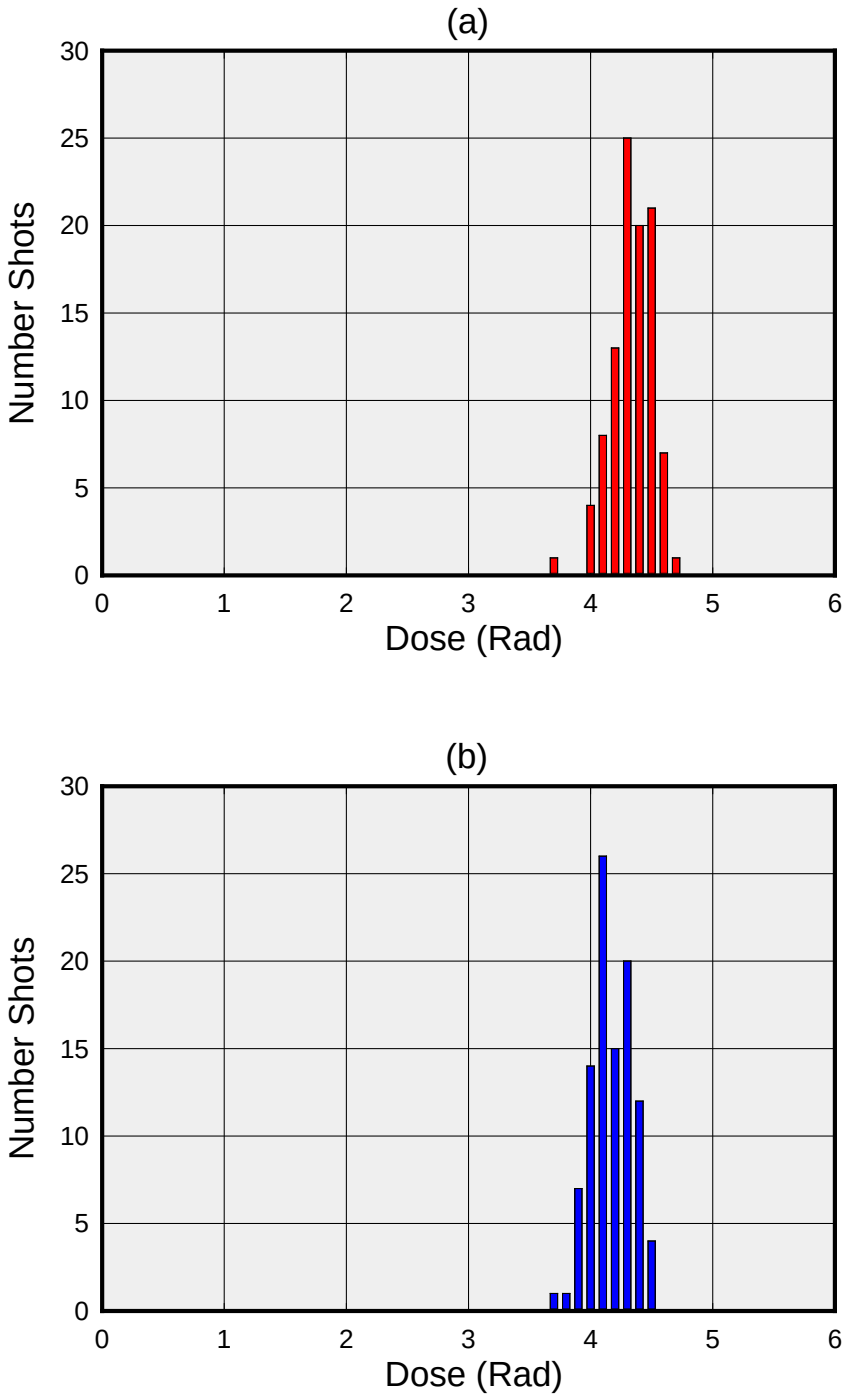


Figure 7. Cygnus dose distribution on Vega for a 100-shot sample: (a) Cygnus 1, (b) Cygnus 2.

CONCLUSION

Cygnus Reliability, Record, and Reproducibility were favorably demonstrated during the project through dose measurements. A summary of Vega performance is given in Tables V and VI below. Execution by the Cygnus team in an elevated state of operational readiness preceding the Vega shot (100 and 10 shot periods) optimized the probability for success on Vega.

On the Vega subcritical shot, Cygnus 1 dose was **4.26 Rads**, and Cygnus 2 dose was **4.15 Rads**.
Therefore dose exceeded the project goal of 4.00 Rads.

The dose results in this report, in combination with timing results and spot size contributed by the Cygnus x-ray imaging diagnostic, prove both Cygnus machines provided a high quality x-ray source for the Vega SCE.

Table V. Vega Performance Summary - Cygnus 1

Shot Type	Period	Percent	Dose (Rad)	Dose (Rad)
		Reliability - Grades/All - Contiguous/Yes	Record - Grades/A^+ & A - Contiguous/No	Reproducibility - Grades/A^+ & A - Contiguous/No
Vega	100 Shots - Historical	100%	4.34	$\pm$ 0.17
Vega	10 Shots - Readiness	100%	4.32	$\pm$ 0.16
Vega	1 Shot - SCE	100%	4.26	$\pm$ 0.00
Design	100 Shots - Historical	99.5%	4.00	$\pm$ 0.40

Table VI. Vega Performance Summary - Cygnus 2

Shot Type	Period	Percent	Dose (Rad)	Dose (Rad)
		Reliability - Grades/All - Contiguous/Yes	Record - Grades/A^+ & A - Contiguous/No	Reproducibility - Grades/A^+ & A - Contiguous/No
Vega	100 Shots - Historical	100%	4.17	$\pm$ 0.16
Vega	10 Shots - Readiness	100%	4.19	$\pm$ 0.14
Vega	1 Shot - SCE	100%	4.15	$\pm$ 0.00
Design	100 Shots - Historical	99.5%	4.00	$\pm$ 0.40